PANIC 2021, Lisbon, 08/09/2021

X-ray spectroscopy experiments on exotic Ξ^- atoms at J-PARC

T. O. Yamamoto (JAEA ASRC [Japan])

for the E07/E03 collaboration

Contents

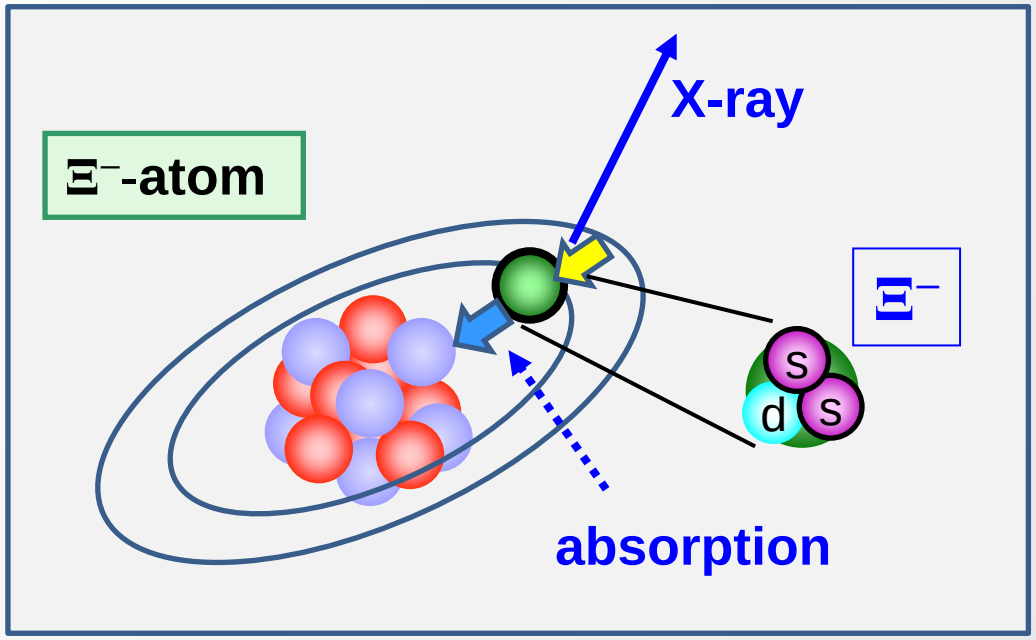
- X-ray spectroscopy of Ξ^- atom
- First try [J-PARC E07]
- Fe Ξ^- atom measurement [J-PARC E03]
  - 1st-phase data taking was completed!
- Future measurement [J-PARC E70]
- Summary

X-ray spectroscopy of Ξ^--atom

We are aiming for

world first measurement of X ray from Ξ^--atom

→ Information on the ΞA optical potential

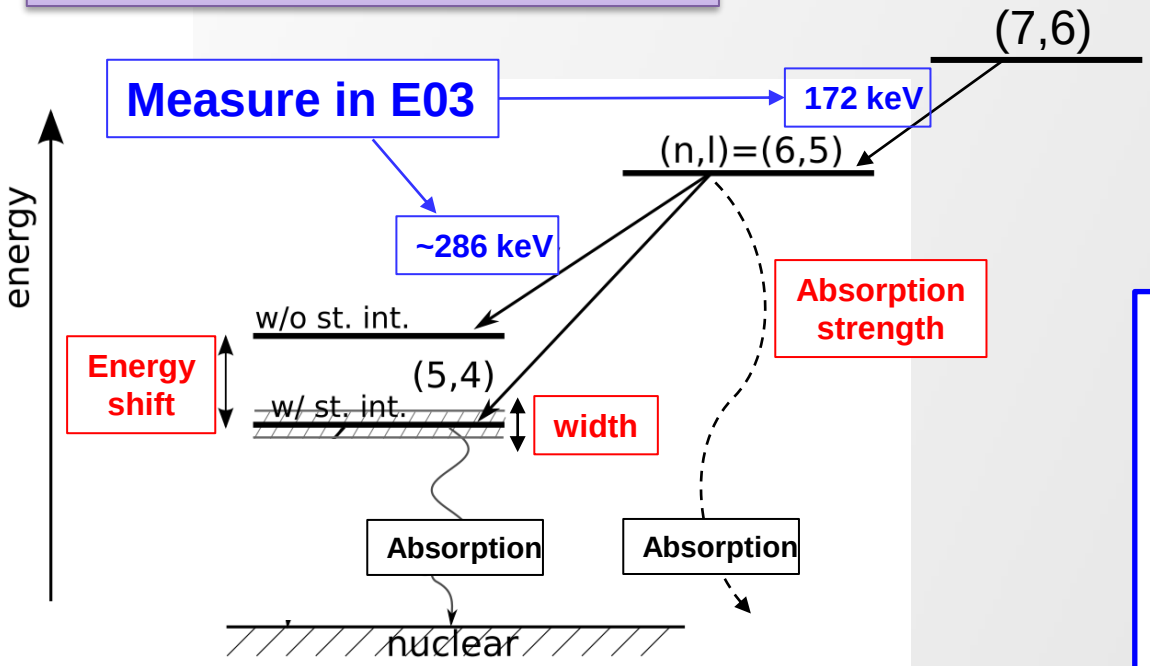


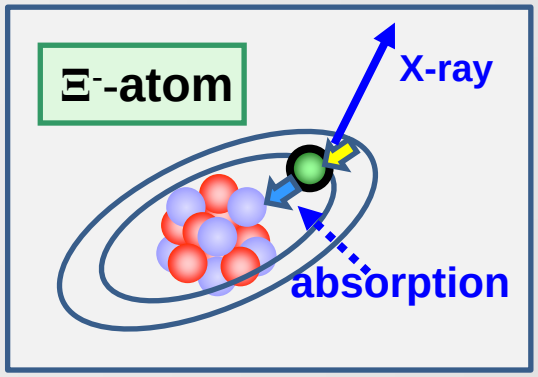
- **Information on (effective) ΞN interaction**
  large baryon mixing?
  (small ΔM(ΞN-ΛΛ)=28 MeV)
- **ΞA interaction and it's A dependence**
  Role of Ξ^- in neutron star?

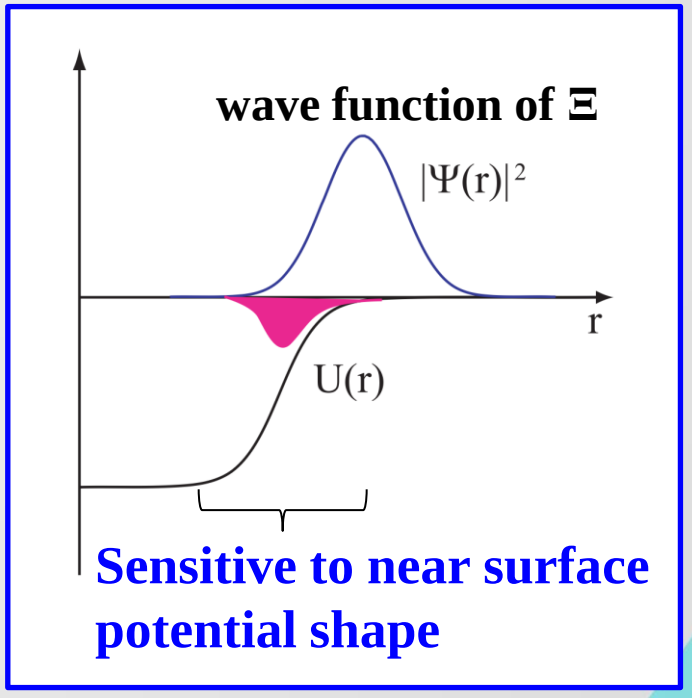
Establishment of experimental method in the J-PARC E03 (Fe-Ξ^- atom)
→ Systematic measurement (over wide mass range) in future

X-ray spectroscopy of Ξ⁻-atom

Level scheme of Fe-Ξ⁻ atom







Measurement of energy shift and width
→ Ξ⁻A real and imaginary term (near surface)

This method has been successfully applied for negative charged particles (π^-, K^-, $\bar{p}$, Σ^-)

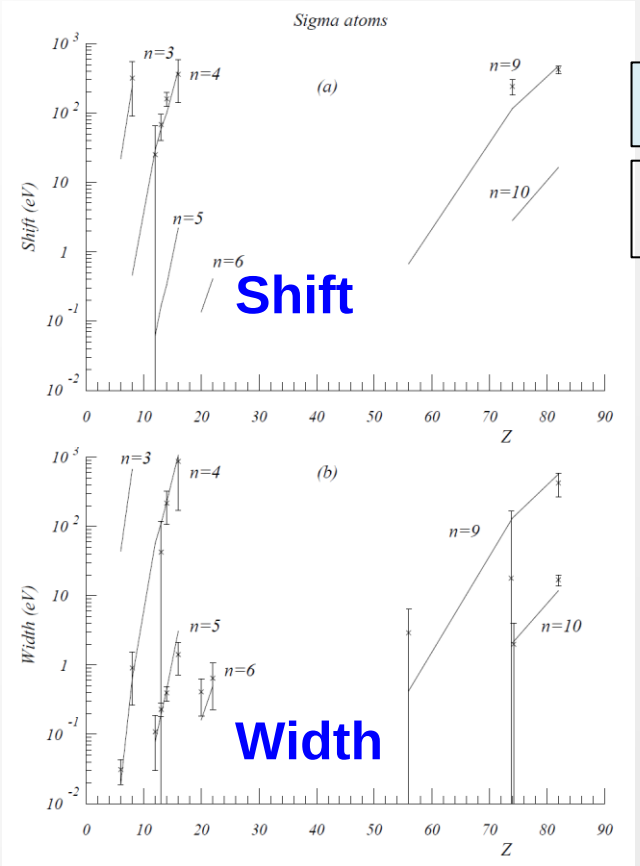
Physics motivation

- **Valuable information on ΞN (effective) interaction**

Need systematic X-ray measurement over wide mass range

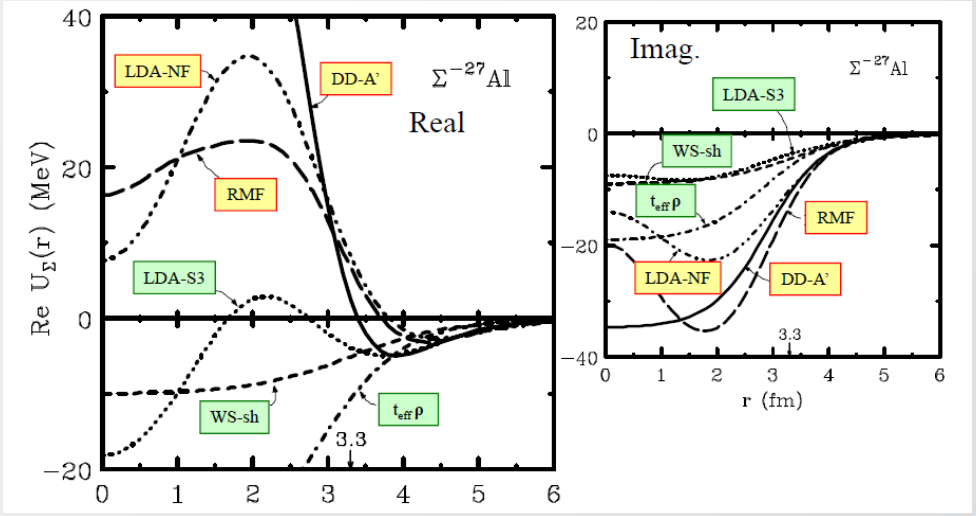
→ **Potential shape, mass dependence**

as in the case of Σ⁻ atom data



Σ⁻ atom data

E. Friedman, A. Gal
the International School of Physics Enrico Fermi (2007)



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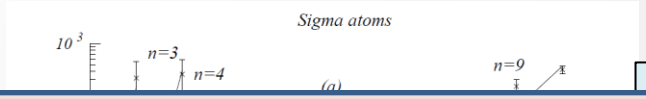


as in the case of Σ^- atom data

Our strategy for Ξ^--atom

No Ξ^--atom data so far

A

C (Z=6)-atom : J-PARC E07(-2017) & future measurement

(also N-atom, O-atom…)

Fe (Z=26)-atom : J-PARC E03 (-2021)

Br (Z=35)-atom :

Ag (Z=47)-atom :

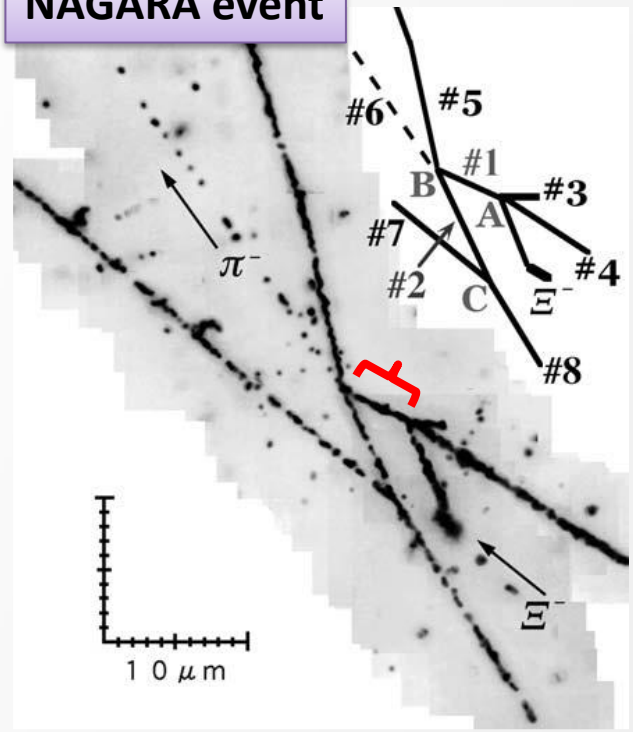
} **Our first try in J-PARC E07(-2017)**

Pb (Z=82)-atom : PANDA (2027+)

Talk of Marcell Steinen
(Sunday, parallel session)

Impact on emulsion data

NAGARA event



Stopped Ξ⁻s form Ξ-atoms before reaction

$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$$^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-.$$

$B_{\Lambda\Lambda}$ = 6.91 ± 0.16 MeV

H. Takahashi et al, Phys. Rev. Lett. 87 (2001) 212502.

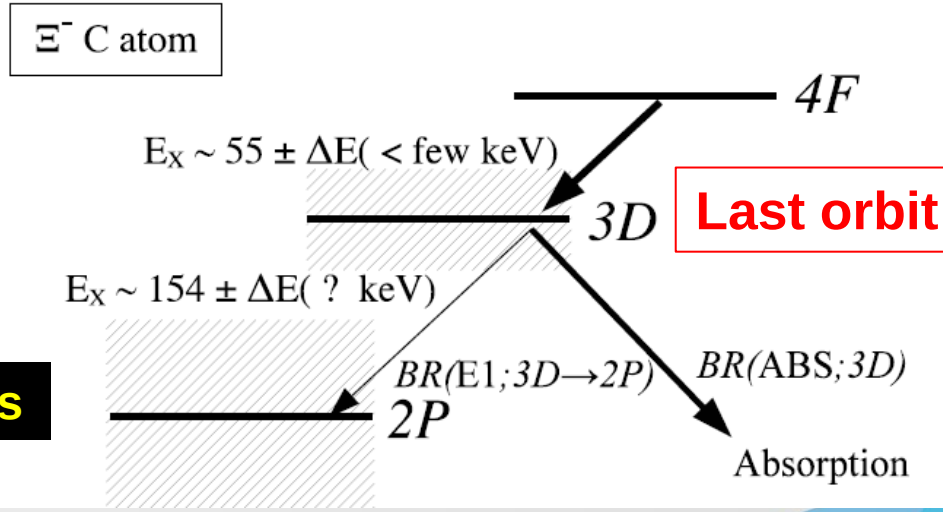
obtained from analysis of both production and decay point

Depends on B_Ξ of C Ξ⁻-atom [B_Ξ = 0.13 MeV] (energy center and error)

Theoretical prediction:

3D absorption is dominant

C. J. Batty, E. Friedman, and A. Gal *Phys. Rev. C59, 295 (2001)*



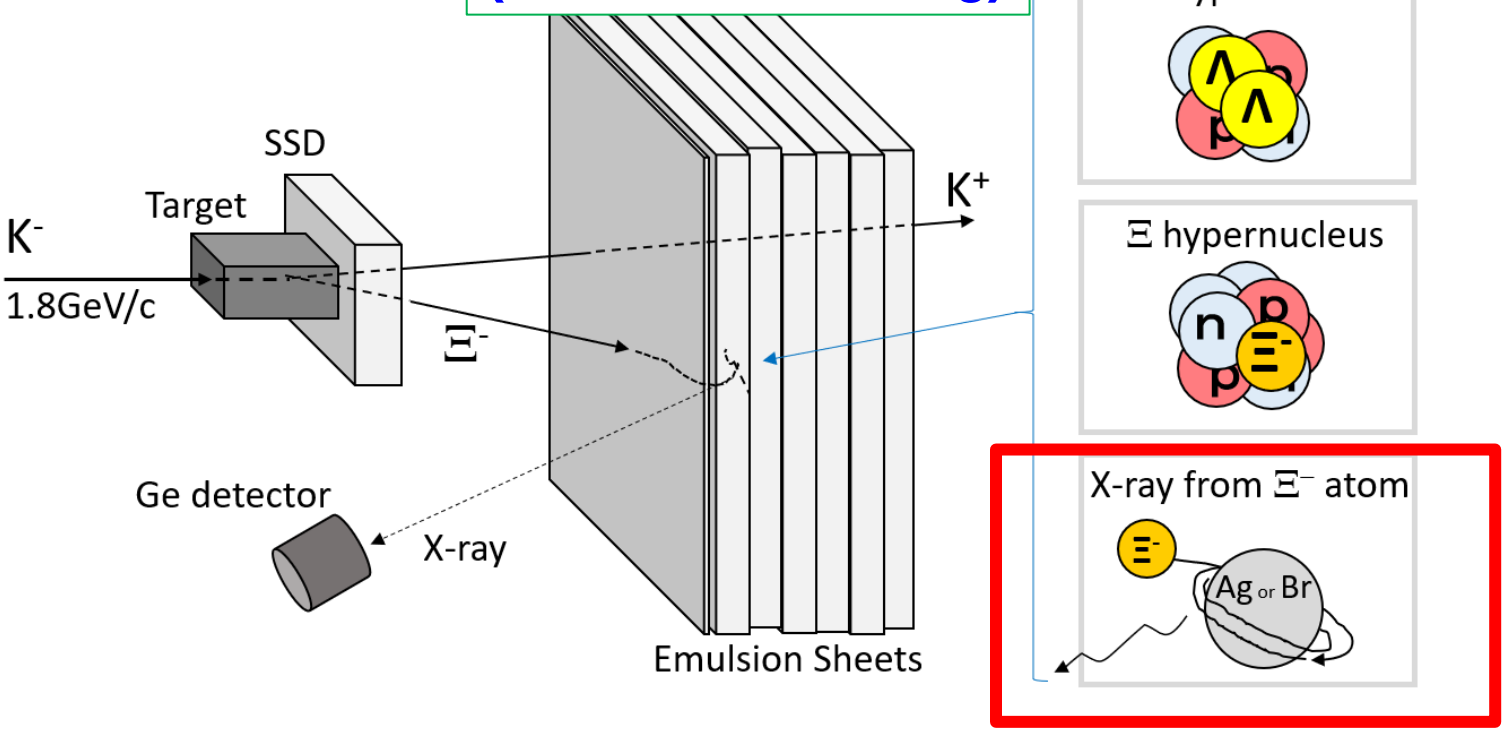
X-ray data will support $B_{\Lambda\Lambda}$ analysis

Our first try in J-PARC E07

Experimental study of double hypernuclei at J-PARC

Done in 2016-2017

Emulsion (H,C,N,O, Br and Ag)



Junya Yoshida (Advanced Science Research Center, JAEA)

On behalf of J-PARC E07 Collaboration

2019 Guilin, China HADRON XVIII International Conference on Hadron Spectroscopy and Structure

Our first try in J-PARC E07

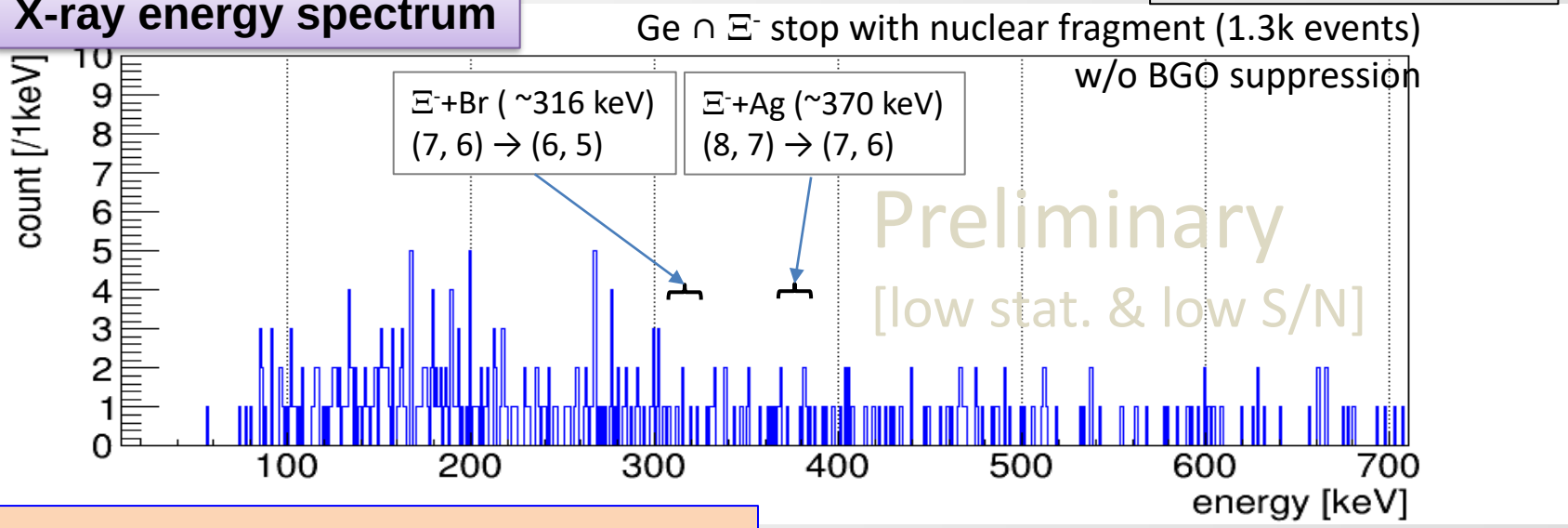
For Ag- and Br-atom

Measurement (1) : Emulsion combined analysis

- **S/N ratio ○ [we can tag Ξ⁻ stop in emulsion]**
- **Yield rate ×**
  - **Low stop prob. (long flight, low density)**
  - **Mixture target (H, C, N, O, Br and Ag)**
  - **Not optimum setup for X-ray detector**

J. Yoshida and M. Fujita
HADRON 2019

X-ray energy spectrum



Emulsion analysis is on going…
→ ~20% of full statistics so far for "analyzed Xi stop events"

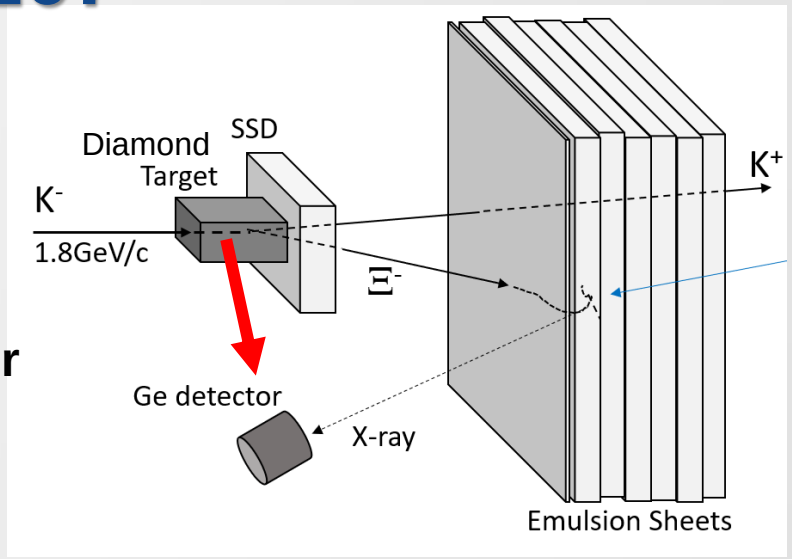
Expected # of X-ray counts = 10-20 (for Ag) w/ full stat.

Our first try in J-PARC E07

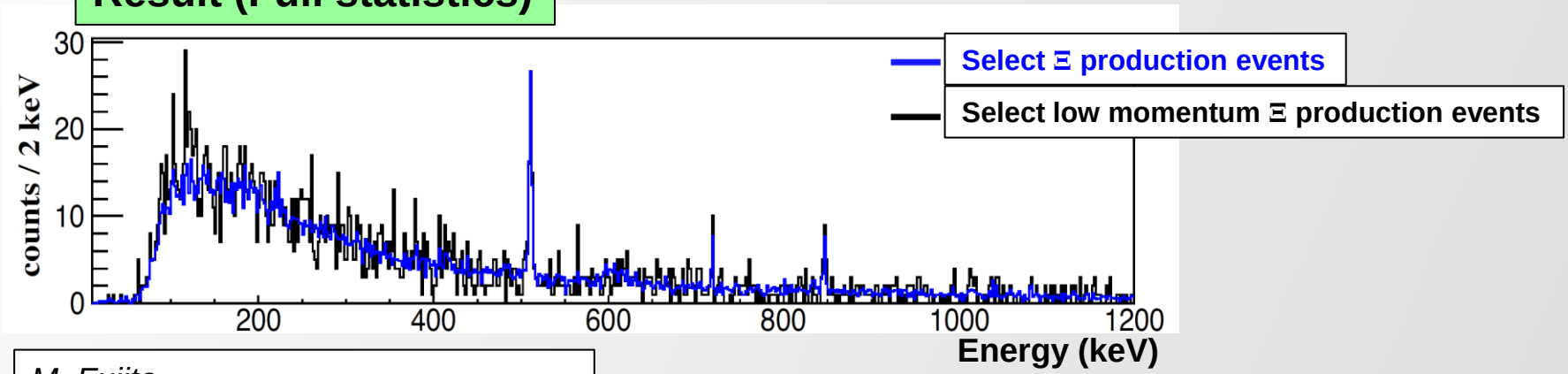
For C-atom

Measurement (2) : w/o emulsion info.

- **S/N ratio △ [only SSD hit rejection]**
- **Yield rate △**
  - **Low stop probability (low density)**
  - **Not optimum setup for X-ray detector**



Result (Full statistics)



M. Fujita
Doctoral Thetis, Tohoku Univ. (2019)

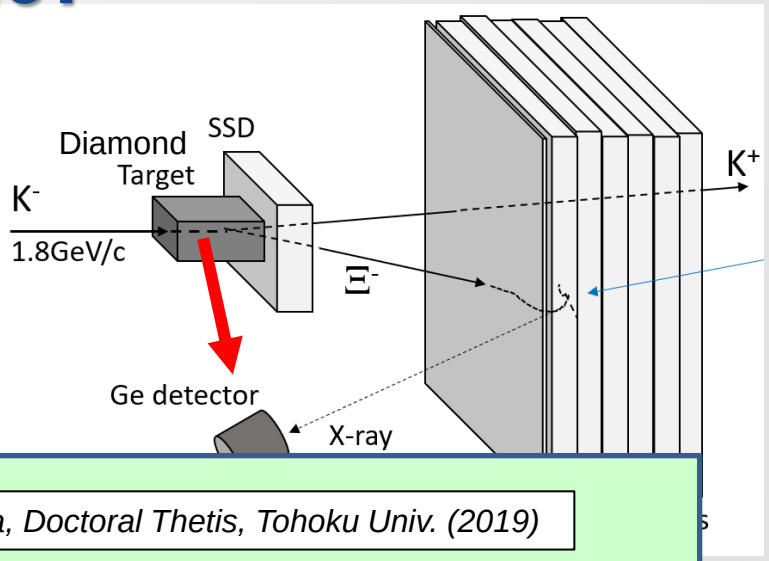
Unfortunately,
no significant peak was observed…

Our first try in J-PARC E07

For C-atom

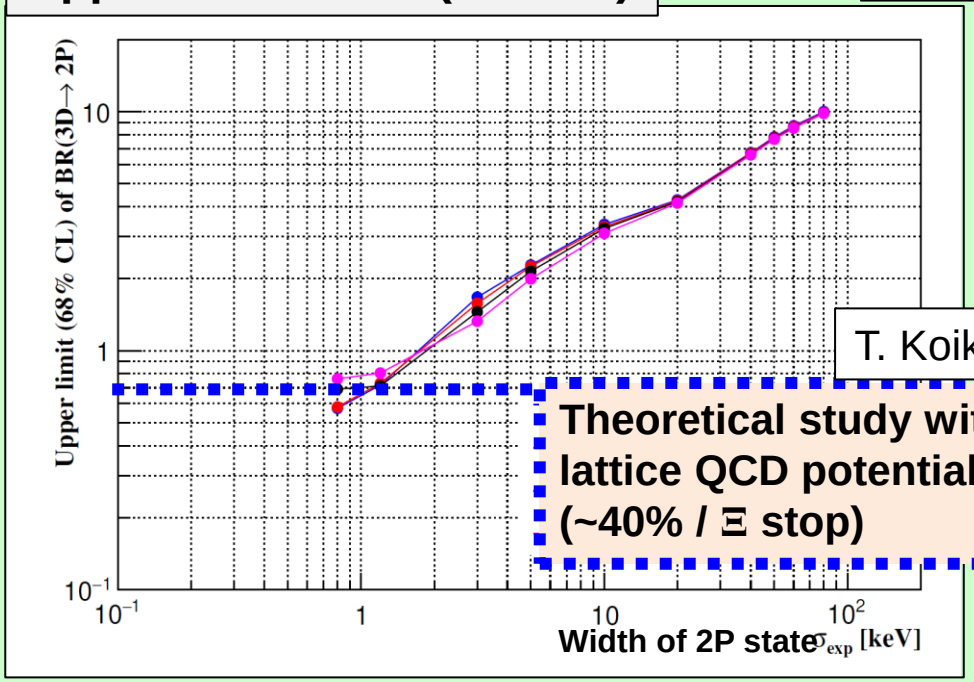
Measurement (2) : w/o emulsion info.

- **S/N ratio △ [only SSD hit rejection]**
- **Yield rate △**
  - **Low stop probability (low density)**
  - **Not optimum setup for X-ray detector**



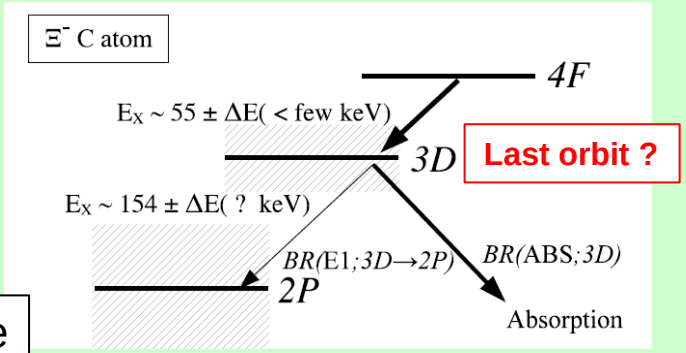
Upper limit for BR(3D->2P)

M. Fujita, Doctoral Thetis, Tohoku Univ. (2019)



T. Koike

Theoretical study with lattice QCD potential (~40% / Ξ stop)

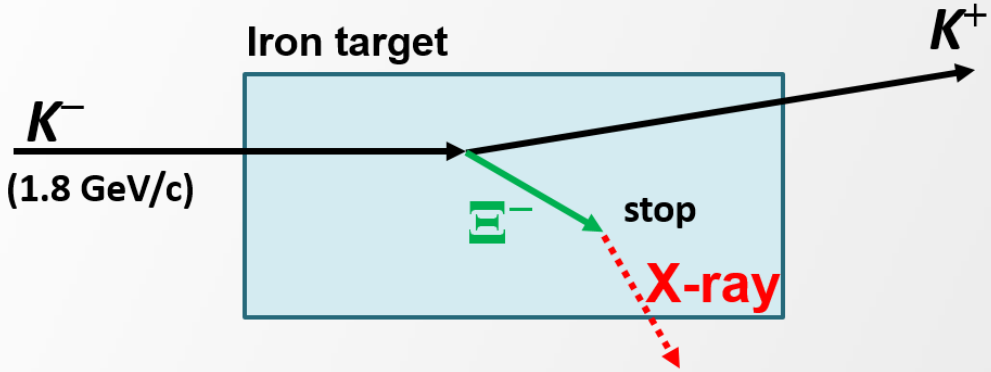


We achieved upper limit close to theoretical prediction

We will retry the measurement for C-atom

Fe Ξ⁻ atom measurement [J-PARC E03]

We are aiming for world first measurement of X ray from Ξ⁻-atom



Feature of the measurement:

- **S/N ratio △**
  [we can not tag Ξ⁻ stop, but high stopping prob.]
- **Yield rate ○**
  - High stop probability
  - Optimum detector setup

Advantage of Fe target

[Technical reason]

Enough dense (~7.9 g/cm^3) for higher stopping probability of Ξ⁻

[Physics reason]

Absorption strength (and width) reported in theoretical case study is suitable for our measurement

Calculated by T. Koike

(5,4) state : ΔE~Γ~ 4keV [W.S. shape potential of -24-3i MeV]

Recent Lattice & ChiralEFT calc.
Shows <1/10 smaller imaginary strength

Experimental setup (E03)

reaction-X ray coincidence experiment

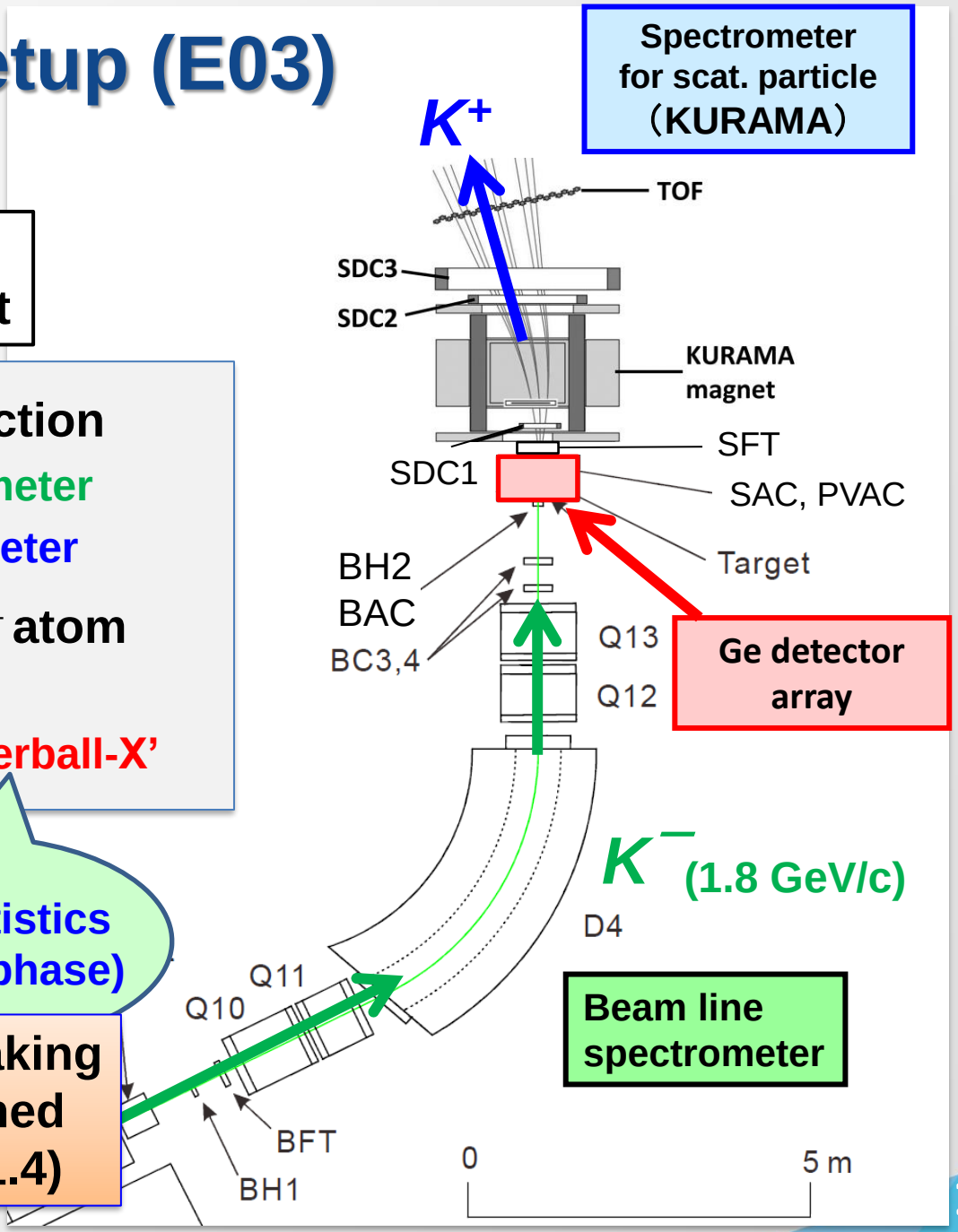
- **Tag $(K^-,K^+)\Xi^-$ production**
  - **Beam line spectrometer**
  - **KURAMA spectrometer**
- **Detect X ray from Ξ^- atom**
  - **Ge detector array**

  Hyperball-J or Hyperball-X'

Full statistics run (2^{nd}-phase)

10% statistics Run (1^{st}-phase)

Data taking finished (2021.4)



Strategy of E03

For Fe-atom

We decided to run with 10% statistics (1st-phase) for not full accelerator intensity

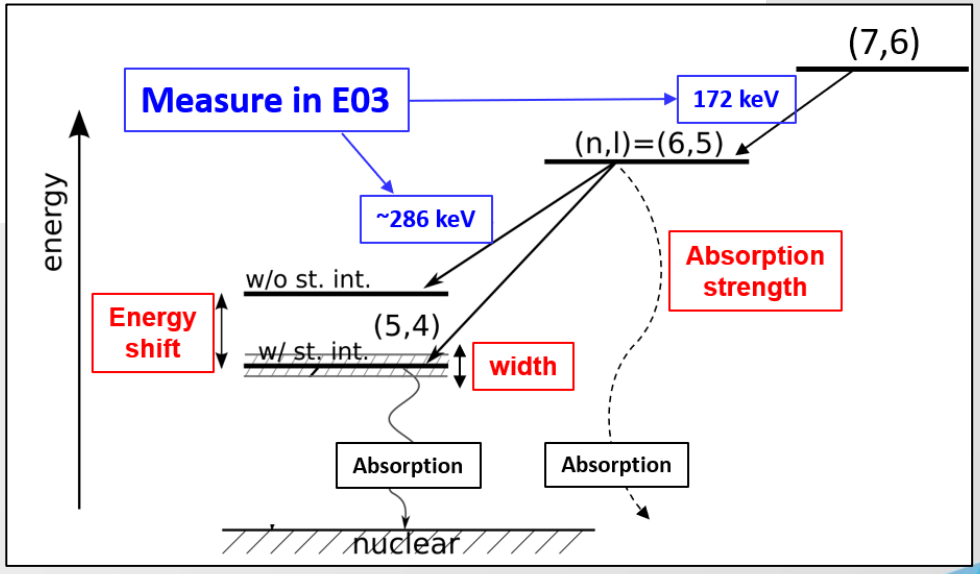
< 1st phase > 10% statistics **(~20 days with present beam power)**

- (7→6) transition will be seen
  → **"World first measurement of X ray from Ξ atom"**
- (6→5) finite shift & width **(if Γ<1 keV)**
- information of absorption strength from (6→5)/(7→6)

< 2nd phase > 100% statistics

- (6→5) shift & width
  (if Γ~4 keV)

Reported from theoretical case study (no strong experimental constrain)



Hyperball-J Ge detector array

will be used in full statics E03 run

Constructed for hypernuclear γ–ray spectroscopy experiment (J-PARC E13 [2013-3015])

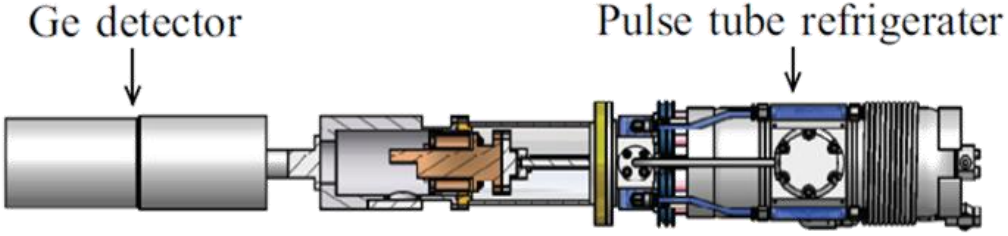
Large photo-peak efficiency

→ ε ~6 % @1 MeV with 32 Ge detectors

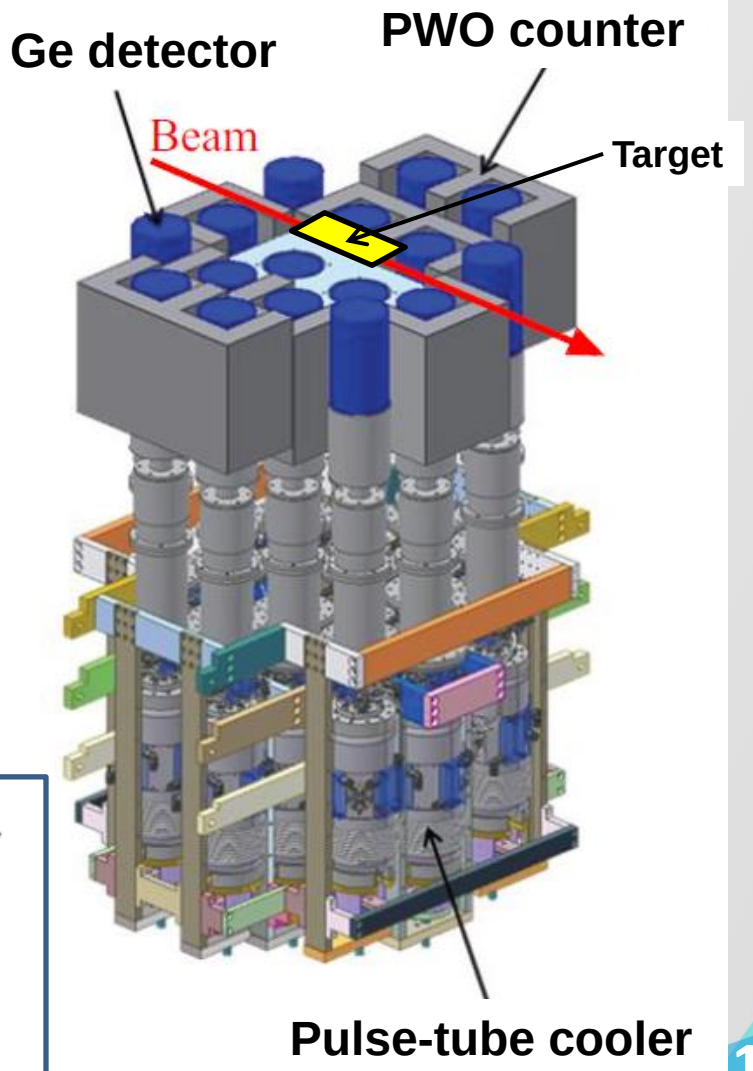
- **Fast readout system**
- **Low temp. Ge detector**
  for radiation hardness
  → Mechanical cooling
- **Fast background suppressor**
  → PWO counter

} for high intensity hadron beam

Developed Ge detector

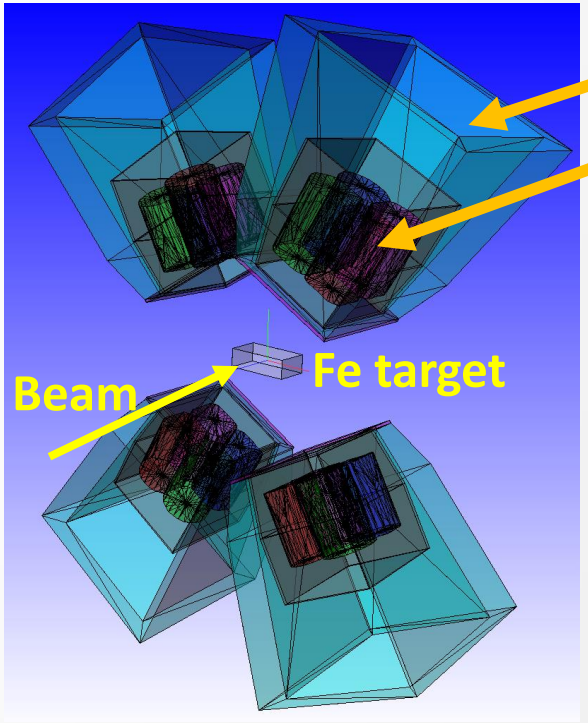


Lower half of Hyperball-J



Hyperball-X' for 1st phase

Constructed in 2020
for E03-1st phase



BGO suppressor

"clover-type" Ge detector (4 segmented crystals)

4 detector units with vertically covered configuration

- Horizontally wide beam profile and target
- Self-absorption of X ray is serious for horizontal direction

	HBX'	HBJ
High rate capability	△ * slow amp. * segmented crystal	○ * fast amp. * large crystal * radiation hardness
Energy resolution	2.5 keV (FWHM)	4 keV (FWHM)

Optimum for low (~250kHz) beam intensity

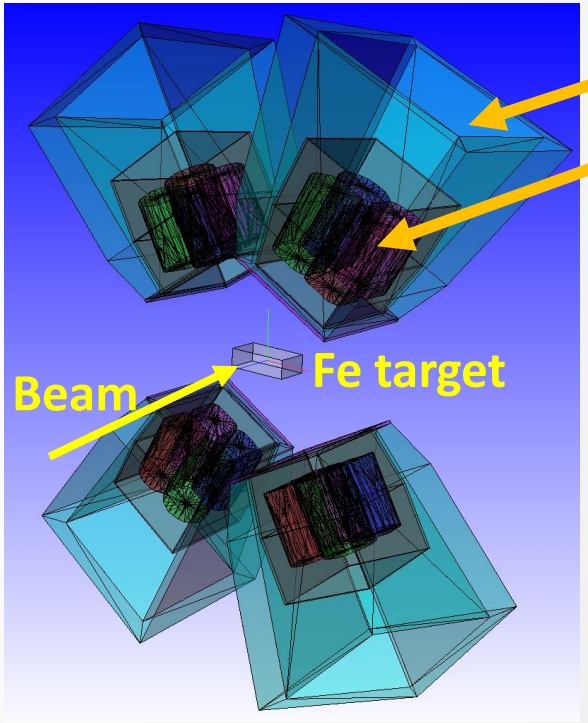
Γ~1keV case,

Higher energy resolution has great merit

- better peak significance
- small error on shift & width

Hyperball-X' for 1st phase

Constructed in 2020
for E03-1st phase



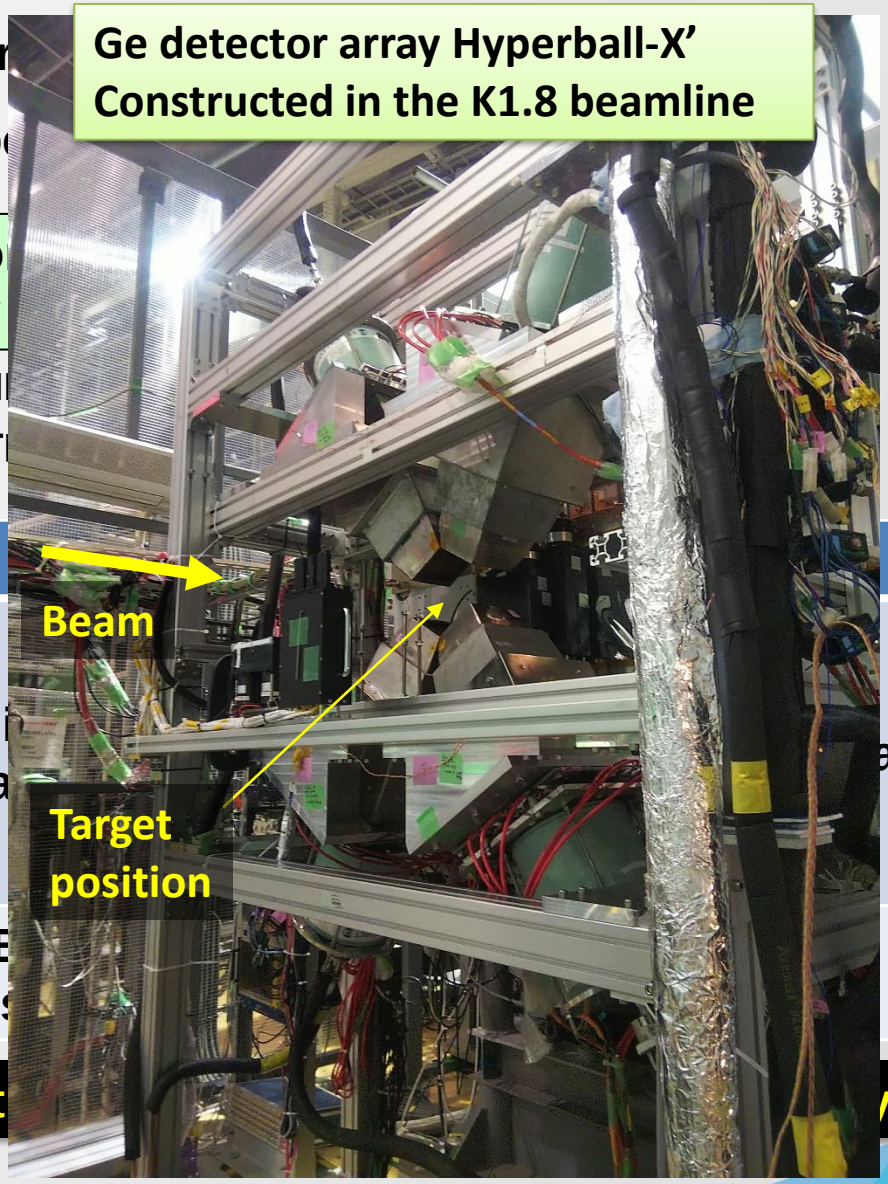
BGO suppr

"clover-typ

4 detecto
vertically

- Horizontal
- Self-absor

Ge detector array Hyperball-X'
Constructed in the K1.8 beamline



Γ~1keV case,
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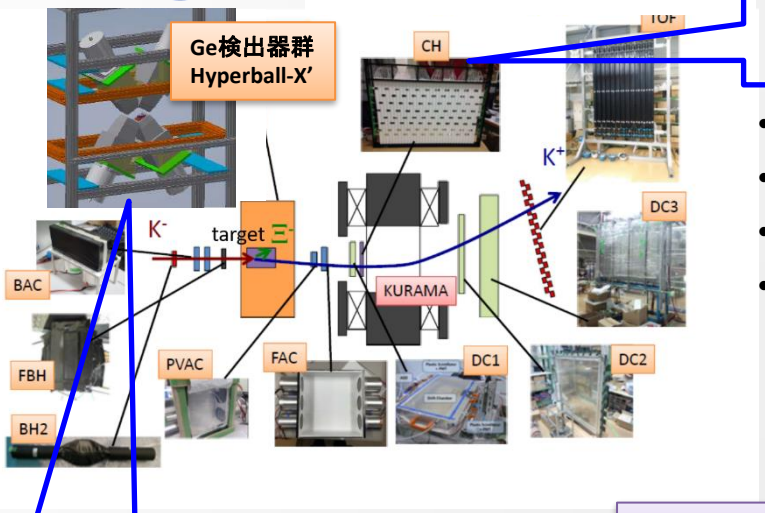
Opt

Detector performance in E03-1st

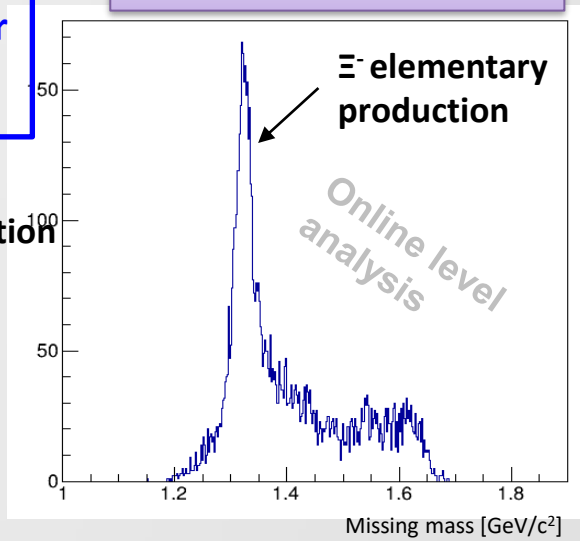
E03 setup @ K1.8



KURAMA spectrometer
(tag Ξ^- production)

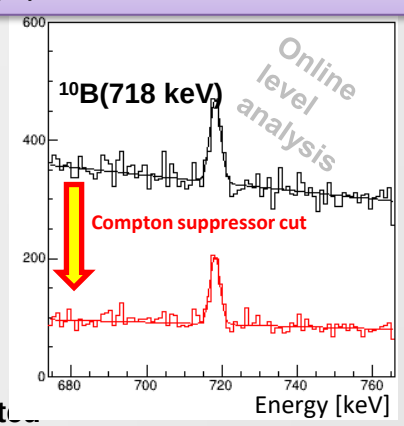
- K-,K+ PID
- Momentum reconstruction
- Reaction vertex
- Production yield

Missing mass spectrum
(CH_2 target)

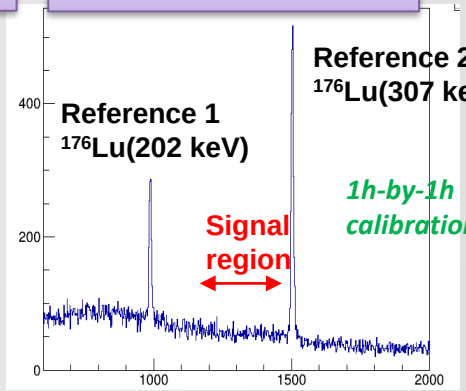


Ge array Hyperball-X'
(detect X rays)

Reaction-γ coincidence spectrum
(CH_2 target)



Calibration spectrum
w/ in-beam calib. trigger



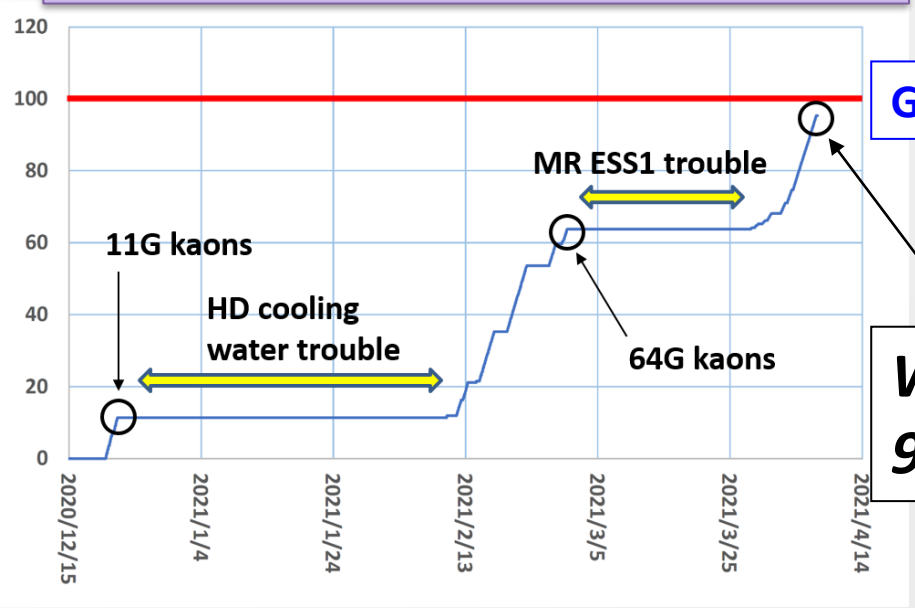
- In-beam energy resolution
  - ~2.3 keV [FWHM] for 307 keV
- Efficiency[geometrical, throughput]
- CH_2 target (^{10}B) gamma-ray
  - Reaction-Ge coincidence measurement
  - also, Iron target gamma ray (847 keV) was detected
- Compton suppressor performance
- Enough statistics for In-beam calibration

Our detector system worked well

E03 data taking

We just finished 1st phase data taking in 2021/4

Integrated # of Kaon beams at Iron target



Goal : 100G

We achieved 95G kaons!

with ~20 days beamtime

We got almost full statistics for 1st phase data taking

Beam condition
K-: 410k/spill, π-: 90k/spill

Data analysis was just started.

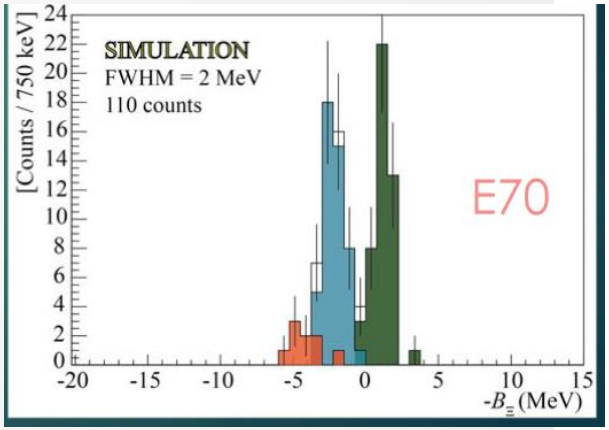
- **Event selection**
- **Calibration**
- **B.G. suppression**

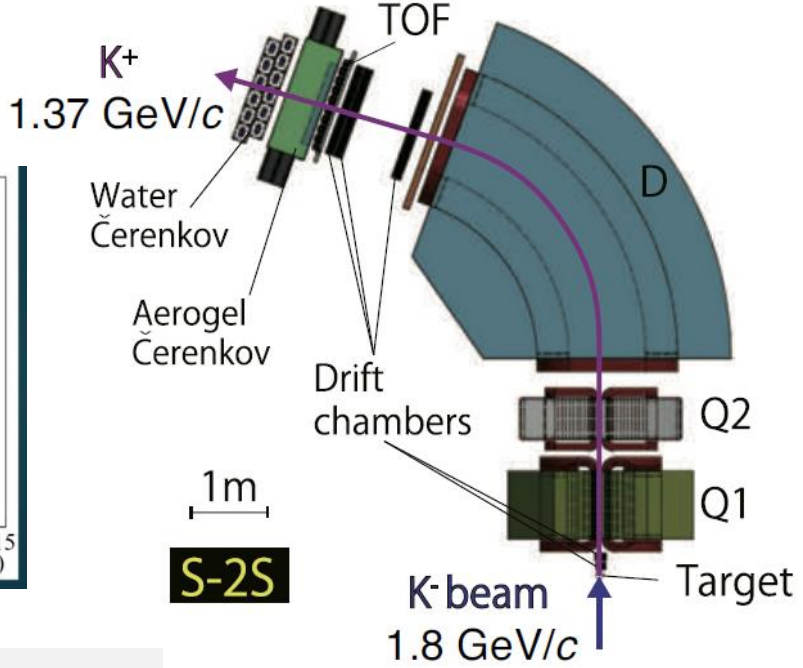
We will report result in near future

Future measurement with S-2S

High resolution Ξ^- hypernuclear spectroscopy with the same reaction.

T. Nagae, J-PARC PAC (2019)





Systematic measurement will be performed:

Target = ^{12}C (E70), ^{7}Li (E75), etc. in future?

Byproduct

Chance for X-ray measurement in parallel

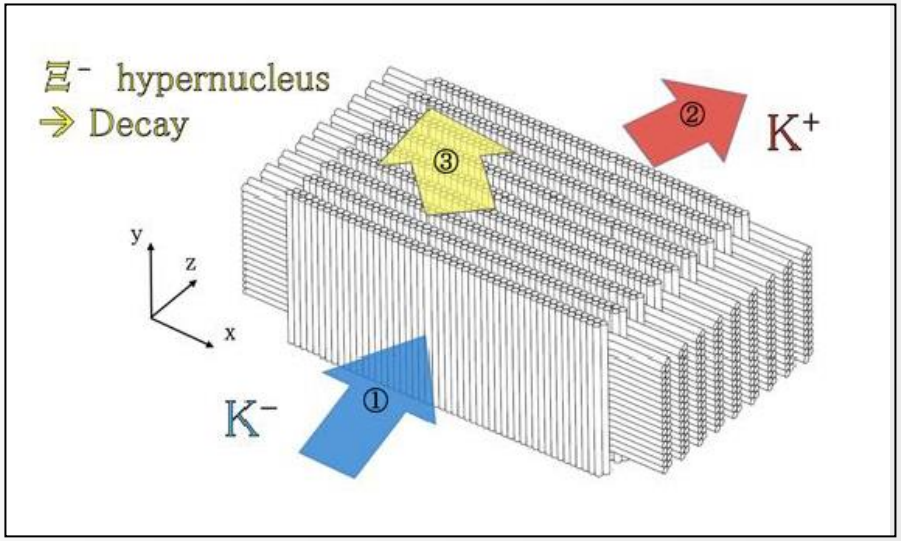
	S-2S
Magnet Configuration	QQD
Acceptance [msr]	55
Magnetic field [T]	1.5
Resolution [FWHM]	5.5 x 10^{-4}
Bending angle [deg]	70

Active fiber target

For C-atom

First target for S-2S experiment: ^{12}C

(E70 physics run in 2022-2023)



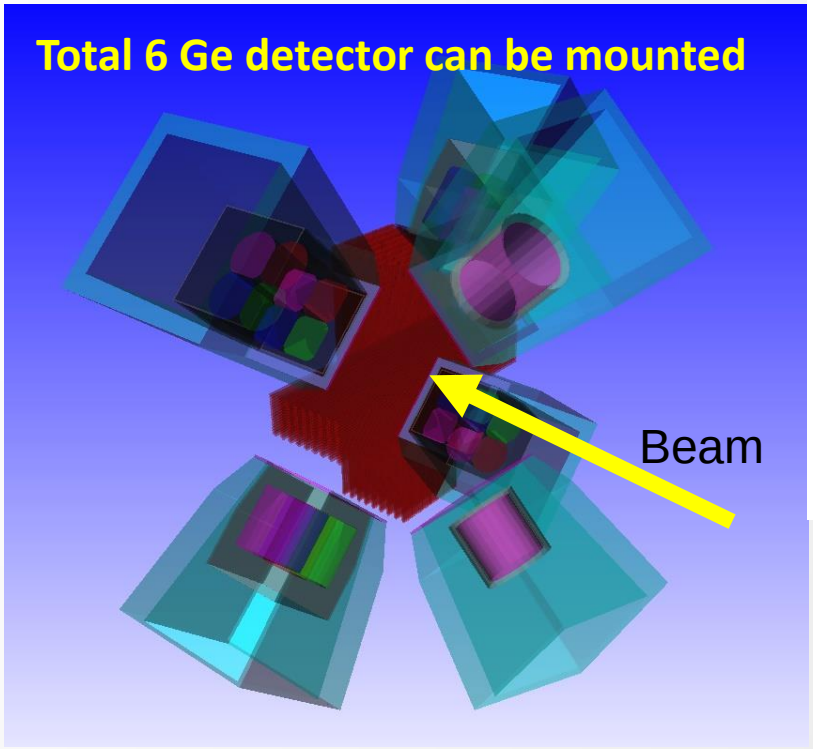
Active fiber target for energy loss correction

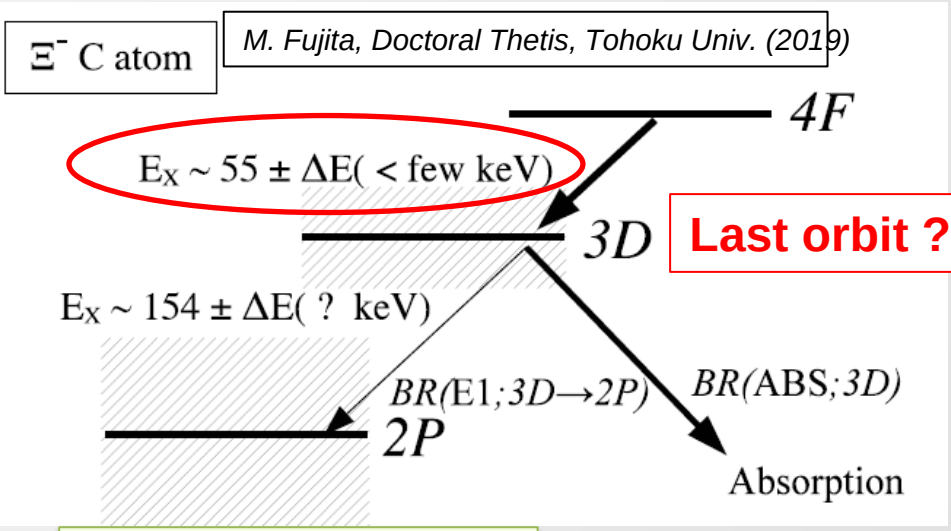
Merit for X-ray measurement

Feature of the X-ray measurement:

- **S/N ratio ○ [we can tag Ξ⁻ stop]**
- **Yield rate ×**
  - **Very low stop probability (low density)**
  - **Smaller acceptance of S-2S**

Second try for C-atom measurement





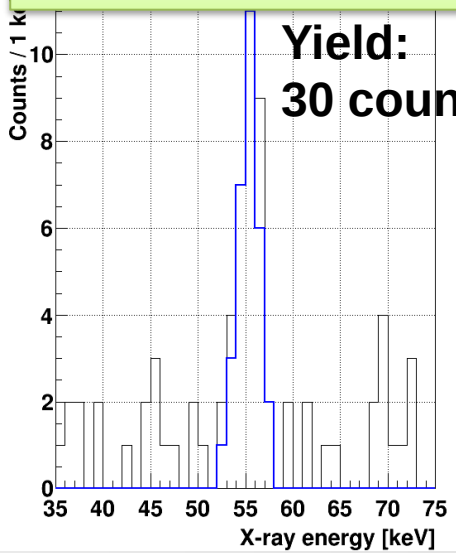
Assumption for yield estimation:

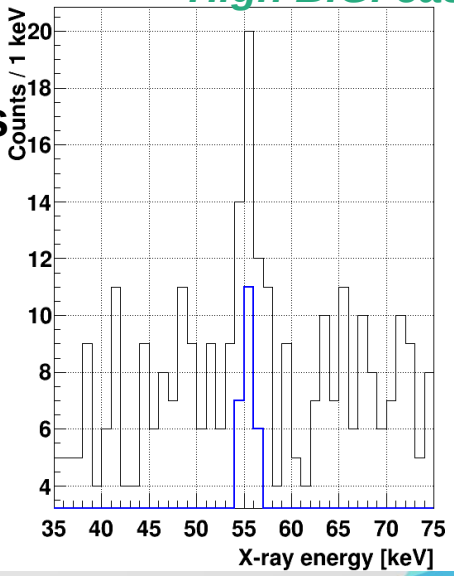
- 30% X-ray yield / Ξstop
  [lower than QCD based calc. (~40%)]
- ~1 month beamtime for E70

We have chance to observe X ray

Expected spectrum

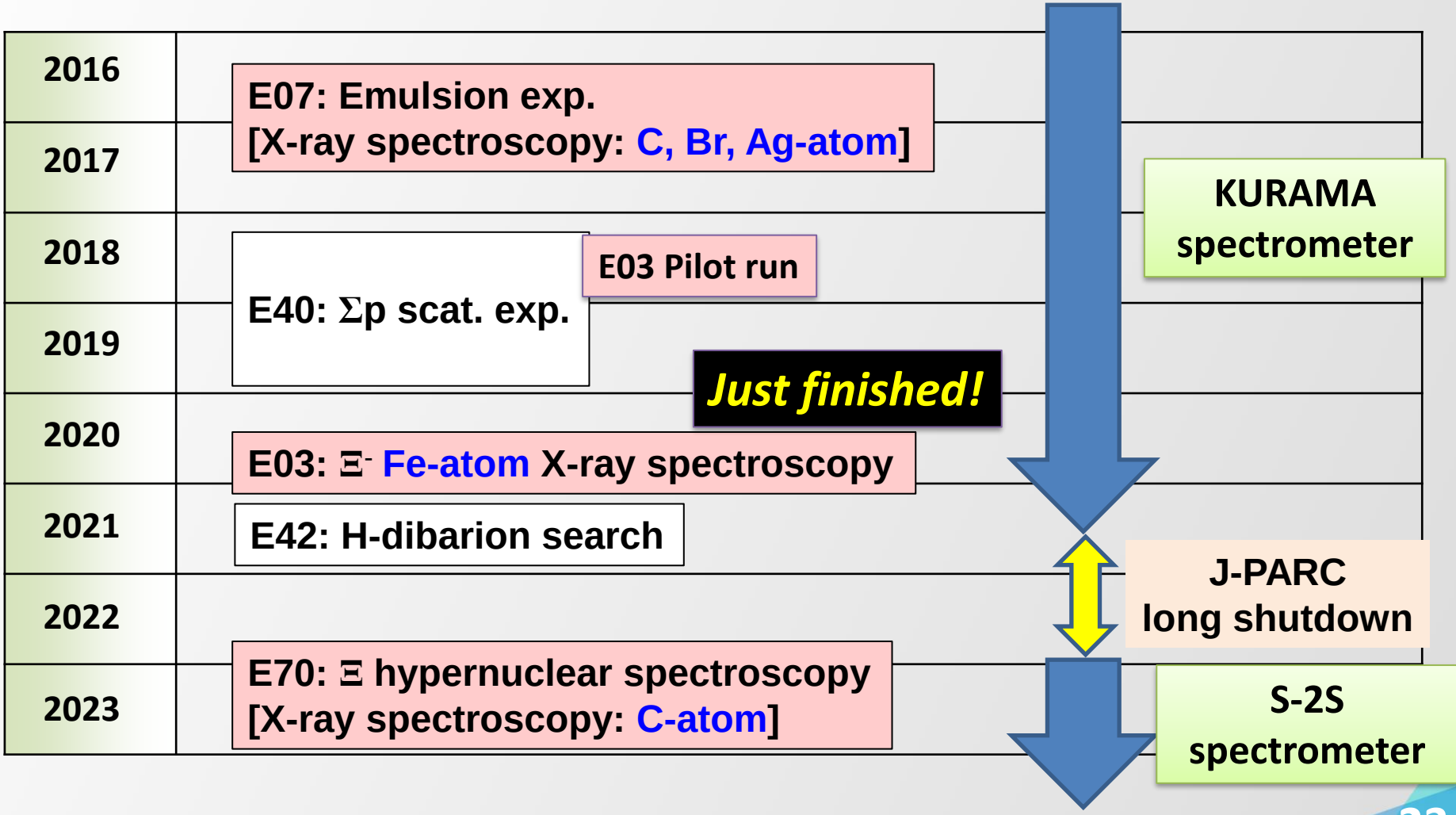
High B.G. case





Timeline of X-ray spectroscopy of Ξ^--atom

at J-PARC K1.8 beam line



Summary

We are aiming for
world first measurement of X ray from Ξ^--atom

→ Information on the ΞA optical potential

- **Test of Experimental technique in J-PARC E07**
  [X-ray spectroscopy: C, Br, Ag-atom]
- **E03 (Ξ^- Fe-atom measurement)**
  2 phase strategy for current ACC condition
  - **1st-phase data taking [2020-2021]** ***Just finished***
- **Future measurement in S-2S exp. (J-PARC E70)**
  [X-ray spectroscopy: C-atom]